Sub-daily northern hemisphere ionospheric maps using the IGS GPS network

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ionospheric total electron content (TEC) data derived from dual-frequency GPS signals from 30 globally distributed IGS network sites are fit to a simple ionospheric shell model, yielding, simultaneously, values for the satellite and receiver biases, and a map of the ionosphere in the northern hemisphere every 12 hours during the period of Jan. 1-15, 1993. RMS residuals of 2-3 TEC units arc observed over the 20-80 degree latitude band, Various systematic errors affecting the TEC estimates are discussed. The capability of using these global maps to produce ionosphere calibrations for sites at which no GPS data arc available is investigated.

Introduction

The Deep Space Network (DSN) is responsible for navigating spacecraft such as Magellan, Galileo, and Ulysses using doppler and range radio metric data. In order to navigate accurately, the radio metric data must be corrected for the dispersive delay effects of charged particles. Ionosphere calibrations arc also required for other purposes such as correcting single-frequency Very Long Baseline Interferometry (VLBI) measurements and verifying the calibration of the TOPEX altimeter. In the past, the DSN has generated ionosphere calibrations using Faraday rotation data or two-frequency Global Positioning Satellite (GPS) delay data from a single GPS receiver. Single-site techniques provide only limited sky coverage and arc sensitive to data gaps,

In order to improve the ionosphere calibrations, the DSN has begun using a world-wide network of GPS receivers to produce global maps of vertical total electron content(TEC). The continuously operating international GPS Service (IGS) network currently has about 30 stations covering a wide range of latitude from Ny Alesund, Norway to McMurdo, Antartica [Melbourne, et al.]. Assuming a network of 30 ground receivers and a full GPS constellation, TEC can be simultaneously measured on approximately 240 lines-of-sight (8 at each ground site). Since the receivers arc distributed around the globe, a large fraction of the "ionospheric shell" is sampled in just a few hours, Thus, such a network can ultimately provide the capability to make a "snapshot" of the global TEC distribution with few-hour temporal resolution, and a time series of such maps will reveal the evolution of the global TEC structure.

Local maps of TEC over single GPS receiver sites using the GPS dual-frequency delays have been obtained previously by several groups including the authors [Royden, ct al., 1984; Lanyi & Roth, 1988; and Coco, et al., 1991], This method assumes that the electron distribution lies in a thin shell at a fixed height above the Earth, and the measured ionospheric delays arc modeled by a polynomial function of shell angular position. Wc have extended this thin spherical shell fitting technique to multi-site GPS datasets using spherical harmonics as a global basis. Daily ionosphere maps of the northern hemisphere have been produced for 23 days in Jan. -Feb. of 1991 and 11 days in Oct. of 1992 [Wilson, ct al., 1992 and Mannucci, ct al., 1992]. These maps were essentially a daily average ionosphere since each fit used 24 hours of GPS data. We are currently investigating several ways to improve the time resolution of the maps so as to fully exploit the potential of the global dataset.

In this paper, the spherical harmonic fitting technique has been used for periods as short as 12 hours. Due to limited ionospheric shell coverage, the time span cannot be reduced further with the present fitting technique. The tradeoff between time resolution and shell coverage will be discussed below. A dataset consisting of 15 days of GPS data (Jan. 1-15, 1993) from 30 globally distributed sites in the IGS network has been investigated for this work. A world map showing the site locations appears in figure 1. Note that only 5 of the sites arc in the southern hemisphere and the northern hemisphere sites are confined to a latitude band from 25-80 degrees, except for the lone equatorial site at Kourou, French Guyana (KOUR). This dataset therefore has limited utility for studying the equatorial anomaly. However, the IGS network has added 5 sites in the past year and the geographic distribution of sites, particularly in South America and Africa, continues to improve with time.

Ionosphere Model and Estimation Technique

The thin spherical shell model was described in detail in Lanyi & Roth, 1988. Briefly, the vertical total electron content (TEC) is approximated by a spherical shell with infinitesimal thickness at a fixed height of 350 km. The TEC is assumed to be time independent in a reference frame fixed to the Earth-Sun axis for several hours. The intersection of the line-of-sight from the receiver to the satellite with the spherical shell defines a "shell" latitude and longitude, where the zero of shell longitude points toward the Sun, The line-of-sight TEC is assumed to be related to the vertical TEC by an elevation mapping function M(E), which is the simple geometric slant ratio at the shell height h:

$$M(E) = \{1 - [\cos E / (1 + h/R)]^2\}^{-1/2}$$

where E is the elevation and R is the radius of the earth, Dual-frequency GPS observations provide measurements of line-of-sight TEC, but are corrupted by instrumental delay biases between the L1 and L2 signal paths in the satellite transmitter and ground receiver. The instrumental bias can be measured for some ground receivers but the satellite transmitter biases must be estimated or obtained from an independent source. The line-of-sight differential delays for the ith receiver looking at the jth GPS satellite can be modeled by the following expression:

$$\tau^{LOS}{}_{ij} = \tau^r{}_i + \tau^s{}_j + M(E_{ij})\ TEC(\theta_{ij}, \phi_{ij})$$

where $\tau^{LOS}{}_{ij}$ is the line-of-sight differential delay, $\tau^r{}_i$ is the bias for the ith receiver, $\tau^s{}_j$ is the bias for the jth satellite transmitter, $M(E_{ij})$ is the elevation mapping function, and $TEC(\theta_{ij}, \phi_{ij})$ is the vertical TEC at shell latitude θ_{ij} and shell longitude ϕ_{ij}. The vertical TEC over the entire globe can then be fit to a spherical harmonic expansion in θ and ϕ, while simultaneously estimating the receiver and satellite biases.

In producing large-scale TEC maps from GPS data, there is a tradeoff between shell coverage and temporal resolution. To achieve adequate shell coverage given a limited number of ground sites and the speed of the GPS satellites, a certain period of time must pass so that the line-of-sight from the ground site to the satellite can traverse a region of the ionospheric shell. However, the ionosphere is changing during this period of time so the data span should be minimized in order to optimize the accuracy and temporal resolution of the maps. Figure 2 shows the shell coverage for data arcs of 24, 12, and 6 hours on Jan. S, 1993. While the longitude coverage for 24 and 12 hour data arcs is adequate, the coverage for 6 hour data arcs is too patchy in longitude to yield a reasonable spherical harmonic fit. Note that for the 12-hour data arc the equatorial coverage spans only half of the longitude range since there is only one equatorial ground site.

The ionosphere model used is obviously a simplification. The notion of "mapping to vertical" only makes sense when horizontal TEC gradients are not too large. The assumption that the ionospheric shell height is constant everywhere is also an approximation. Simulations with Chapman profiles show that the functional form for the thin-shell mapping functions actually approximates the mapping function for distributed profiles as long as the height is chosen correctly [Hajj, G., 1993]. But choosing the incorrect height can lead to a biased estimation of vertical TEC along a satellite track.

Another problematic assumption is that the ionosphere is independent of time over several hours in the Sun-fixed reference frame. The ionosphere at a fixed shell location will vary in time as a result of variations in the solar flux and other dynamics such as traveling ionospheric disturbances. More importantly, a line of constant geomagnetic latitude varies in time by ±11 degrees over 24 hours as expressed in the Sun-fixed longitude and equatorial latitude shell coordinate system. Thus, the longer the span of data in a fit, the more one is averaging over n~agnctically-influenced variations in the ionosphere.

The accuracy of the ionospheric TEC maps obtained from GPS data is directly affected by uncertainties in the satellite and receiver biases. These can be estimated along with the ionosphere since they do not share the same elevation angle dependence as the TEC. Since the elevation mapping function is only approximate and the ionosphere at a fixed shell location is changing during the time span of the fit, the ionosphere may be systematically mismodeled, leading to an improper separation of the elevation-dependent TEC from the elevation-independent biases. As a result, the bias values obtained from any one fit may be corrupted by ionospheric mismodeling. However, the biases are constant on a time scale of weeks to months so better bias values can be obtained by averaging values from many fits over 10-15 days. To further reduce the effects of ionospheric mismodeling, the estimation procedure can be applied using only nighttime data when the ionosphere is relatively constant in time and therefore less susceptible to modeling errors. Nighttime data are defined to be those observations with ecliptic shell longitudes in the nighttime quadrant opposite the sun.

The following estimation strategy is used. Each multi-site data arc is fit in a two-step process: first, the nighttime data alone are fit to determine receiver and satellite biases, and then, fixing the biases at average values obtained from nighttime fits performed over 10-15 days, the full daytime and nighttime dataset is used to estimate the global ionosphere. In both steps, the vertical TEC is modeled by 8th-order spherical harmonics. only observations with elevation angles above 10 degrees (as seen from the receiver) have been used. For a 2-minute data rate from 30 receivers, a full 12-hour fit consists of approximately 60,000 observations. Since the observable is only sensitive to the sum of the receiver and satellite biases, several of the receiver biases are constrained tightly (a priori standard deviation of 1 nanosecond) to values based on periodic receiver calibrations, while the rest of the receiver biases and all of the satellite biases are essentially unconstrained. This strategy allows one to determine absolute levels for the satellite and receiver biases and it reduces sensitivity to a single erroneous receiver calibration.

Results

Multi-site fits of the GPS data from 30 lGS sites were performed for the period of Jan. 1-15, 1993. Since the majority of the sites arc in the northern hemisphere, results arc presented only for a limited latitude band of 20 to 80 degrees. A contour map of vertical TEC obtained from a 24-hour fit on Jan. 4, 1993 is shown in figure 2. The units arc the usual TEC units of 1016 electrons/meter^2. Note the peak in the ionosphere near zero degrees longitude (the sun axis) and the fall-off at nighttime. Figure 4 shows contour maps of three 12-hour fits covering the period of 00:00 UT on Jan. 4 to 12:00 UT on Jan. 5, These maps arc representative of the thirty 12-hour maps produced for the 15 day period. The temporal evolution of ionospheric TEC can bc investigated by examining a time series of global TEC maps. Using a false-color representation of TEC, a color ionosphere movie has been produced from the sequence of thirty 12-hour maps. The progressive change in the ionospheric structure is quite evident in the color movie,

To determine the accuracy of the maps, a map has also been made of the vertical residual ionosphere (observed TEC mapped to vertical minus the fit). Figure 5a shows a gray-scale map of the vertical root-mean-square (RMS) residuals for the 24-hour fit shown in figure 3. The map is formed by accumulating the RMS of the residuals into a one-by-one degree grid in latitude and longitude. White boxes represent grid squares for which there arc no data as a satellite track never passed through that square. The residuals range from O to 20 TEC units but most arc in the range of O (light gray) to 10 (black) TEC units. The total RMS of the residuals is 4.3 TEC units. Note that the residuals arc below 5 TEC units nearly everywhere in the 20-80 latitude band. Only in a localized region near 20 degrees latitude do the residuals rise above 10 TEC units. The vertical RMS residuals for the 12-hour map in figure 4a arc shown in figure 5b. The total RMS of these residuals is 2.1 TEC units. Note that the residuals for the 12-hour map arc smaller than those for the 24-hour map, as expected since for the 12-hour fits there is less time-averaging than for the 24-hour fits. For the 24-hour fit, there can bc two observations at the same shell position separated by nearly 24 hours. If the ionosphere has changed substantially, the two observations will not bc consistent and the fit cannot match both of them, resulting in a large residual. This effect may also account for the large residuals in the lower latitude region of the map, since in this region variations duc to the magnetic pole rotation arc expected to bc largest.

Another way to check the robustness of the estimation strategy is to remove onc or more sites from the dataset, perform a tit with the remaining sites, and then calculate the vertical residuals for the observations at the removed sites. The result is a measure of how well the maps predict the TEC at shell locations where there arc no data, Figures 6 shows a plot of the Usuda vertical residuals versus shell longitude for a 24-hour fit on Jan. 5 excluding the Usuda data. The residuals arc essentially unchanged when the data from Usuda arc added to the fit. The RMS of the residuals without Usuda data is 2.8 TEC units; with Usuda data it is 2.6 TEC units.

Producing global maps gives onc the capability to predict the vertical TEC at a site with no GPS receiver (or no data that day) by using GPS data from remote sites. Figure 7a plots the vertical TEC directly above the Goldstone (GOLD on figure 1) receiver site versus time for the 24 hours of Jan. 5 as predicted by five different fits: (1) a single-site fit of Goldstone data, (2) a 24-hour global fit including the Goldstone data, (3) a 24-hour global fit excluding the Goldstone data, (4) a pair of 12-hour global fits including the Goldstone data, and (5) a pair of 12-hour global fits excluding the Goldstone data. The five predictions agree to a fcw TEC units. Figure 7b shows a similar plot of the five predictions for the TEC above the Usuda site. The Usuda site is more isolated than the Goldstone site, but for the 24-hour global fits the agreement with the single-site fit is still quite good since Usuda's latitude band is well covered by other sites.

The effect of choosing an incorrect elevation mapping function has been investigated by performing the estimation procedure with a different elevation-angle cutoff. Two 24-hour maps were made using 10 and 20-degree elevation angle cutoffs, The difference map shown in figure 8 was formed by differencing two one-by-one degree grids, The difference grid points have a mean of -0.14 TEC units and a standard deviation of 0.85 TEC units, The map has been restricted in latitude range to 30-80 degrees since the larger elevation cutoff reduces the coverage severely in the latitude range 20-30 degrees. Note that the difference varies smoothly between positive and negative values. This could correspond to a smoothly varying error in shell height over the given regions, For both maps, a constant shell height of 350 km is assumed, If the "effective" shell height is larger than 350 km, then mapping errors at low-elevation will cause the ionosphere to be underestimated. If the shell height is smaller than 350 km, the ionosphere will be overestimated.

Conclusions

The IGS network provides a unique opportunity to continuously monitor total electron content on a global scale. While the current network has limited equatorial and southern hemisphere coverage, more receiver sites will come on-line in the near future. Larger, more uniformly distributed networks will provide denser longitudinal coverage for shorter data arcs, enabling ionosphere mapping every 3 to 6 hours. Since the IGS network is permanent and continuously operating, sub-daily ionosphere maps could be produced continuous y.

The present spherical harmonic ionosphere model limits the maps to a time resolution of 12 hours or longer. Efforts arc under way to improve the time resolution by using a better set of basis functions. A disadvantage of spherical harmonics is that they are non-zero over the entire sphere: they have "global support". For investigating ionospheric behavior over time scales much shorter than 12 hours, it will be necessary to use basis functions with "local support", that is basis functions which arc non-zero over a limited area of the shell. This will produce more accurate maps when coverage is sparse.

As wc gain more experience with this technique, wc anticipate that a more physical or empirical ionosphere parameterization (e.g., Bent, et al, 1976.) will be required to model the high-latitude and equatorial ionospheres.

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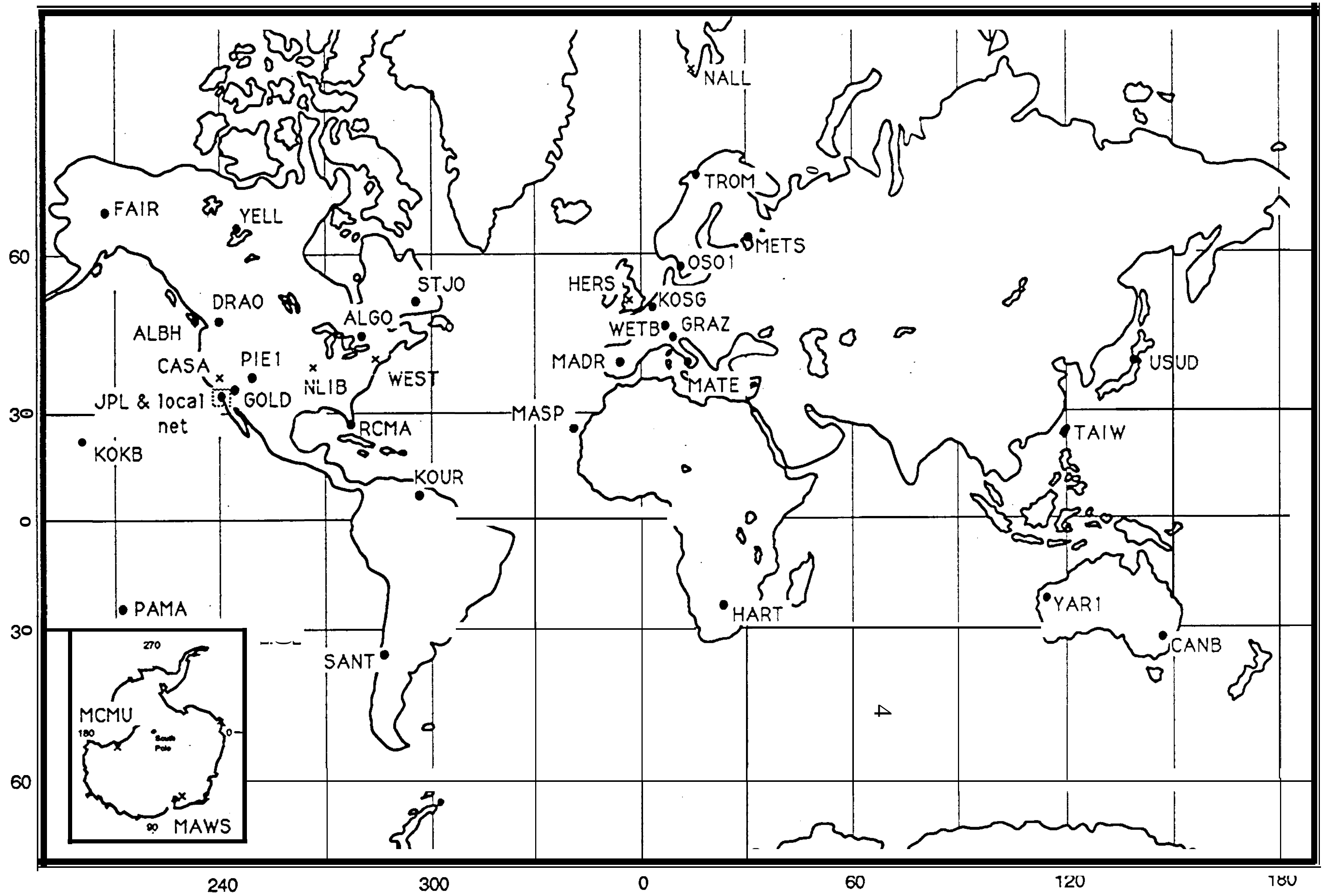


IGS GPS Receiver Network

● Rogue Receiver Network For January 1993

× C ⇐rently Operating Receivers as of March 1 1993

Figure 1. *This map shows the receiver locations for the International GPS service. The receivers at the locations denoted by a filled circle provided data used in this paper.. Additional locations are available as of March 1, 1993 and these locations are denoted by an x-mark.*

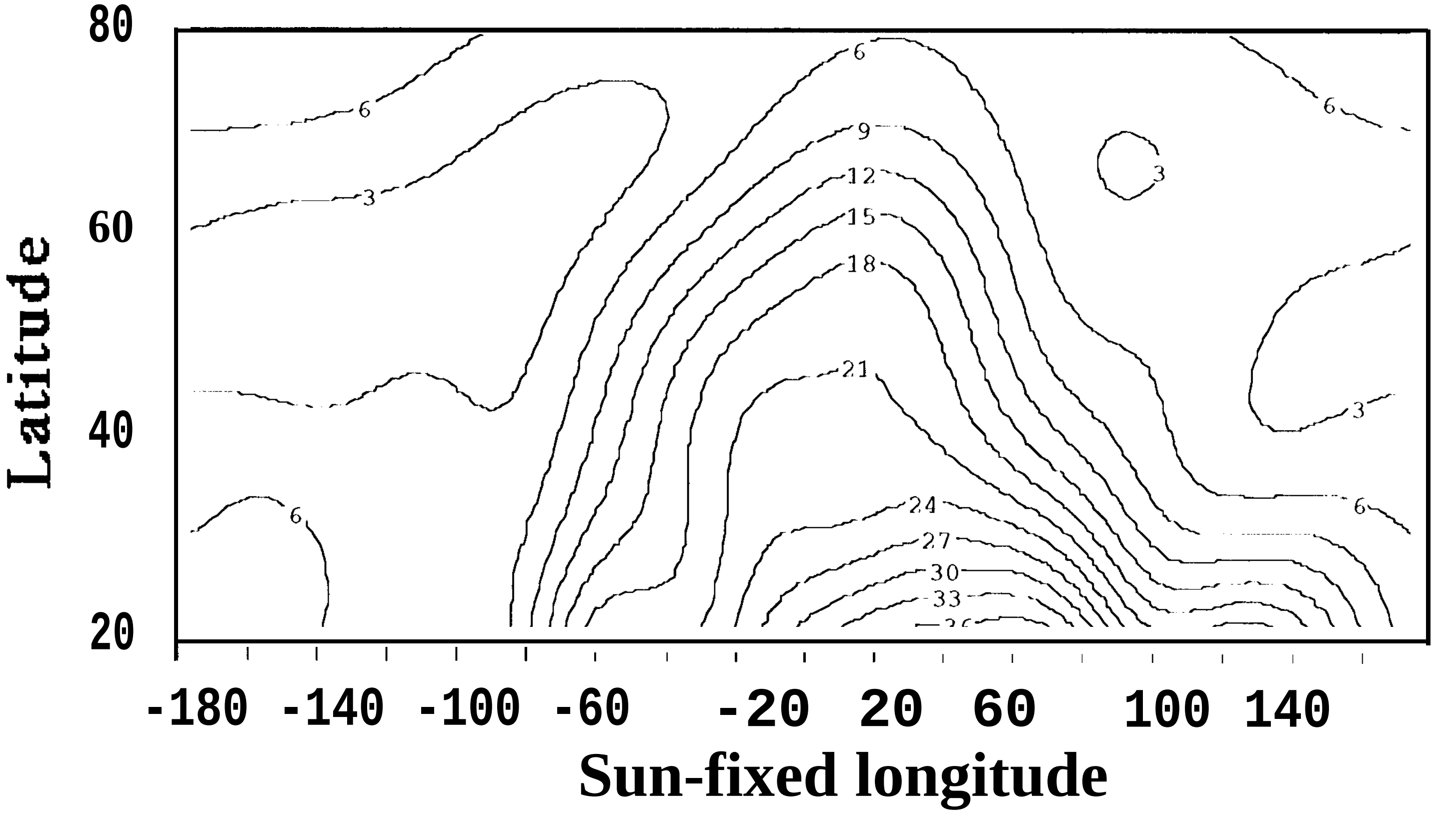


Figure 2 — Global ionospheric TEC distribution for January 4,1993 derived from a 24-hour fit, Contours are labeled in units of 10^{16} el/m^2.

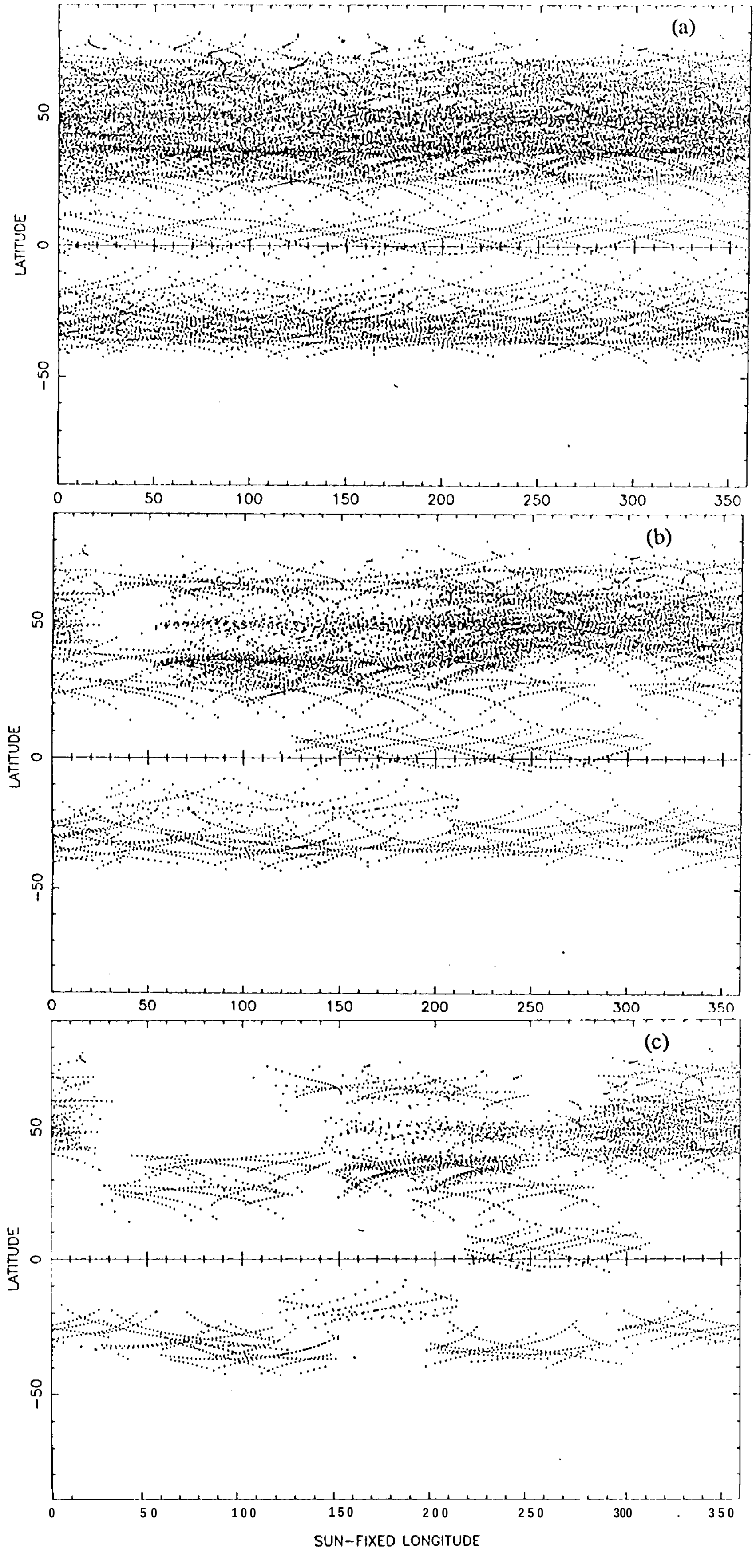


Figure 3. *Fig. 3 shows "coverage plots" for the reciever network of Fig. 1 (filled circles only) for three lime intervals on January 5, 1993. A point is plotted for each shell intercept point made between a receiver and transmitter. The standard "sun-freed" co-ordinate system is used for these plots: O degrees longitude is the Sun-Earth direction and [he Earth rotates underneath. The latitude of this system is the same as geographic. Fig. 3a which covers the period 00:00-24:00 UT on January 5. A single receiver in the equatorial region (Kourou, French Guyana) provides sparse coverage there. In Fig. 3b, the shell coverage for the period 00:00-12:00 UT is shown. In Fig. 3c the coverage for the 6-hour period of 06 :00-12:00 UT is shown.*

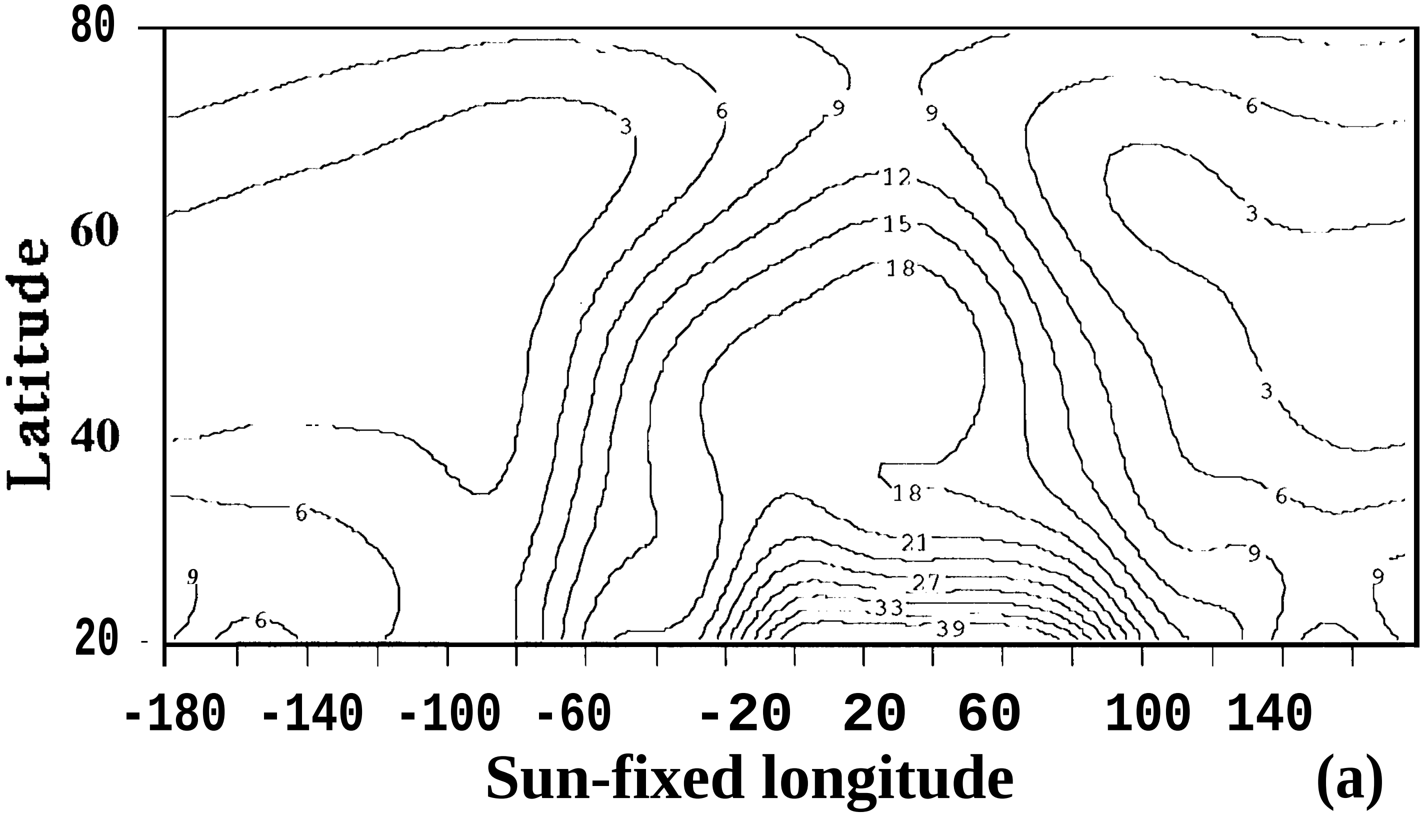
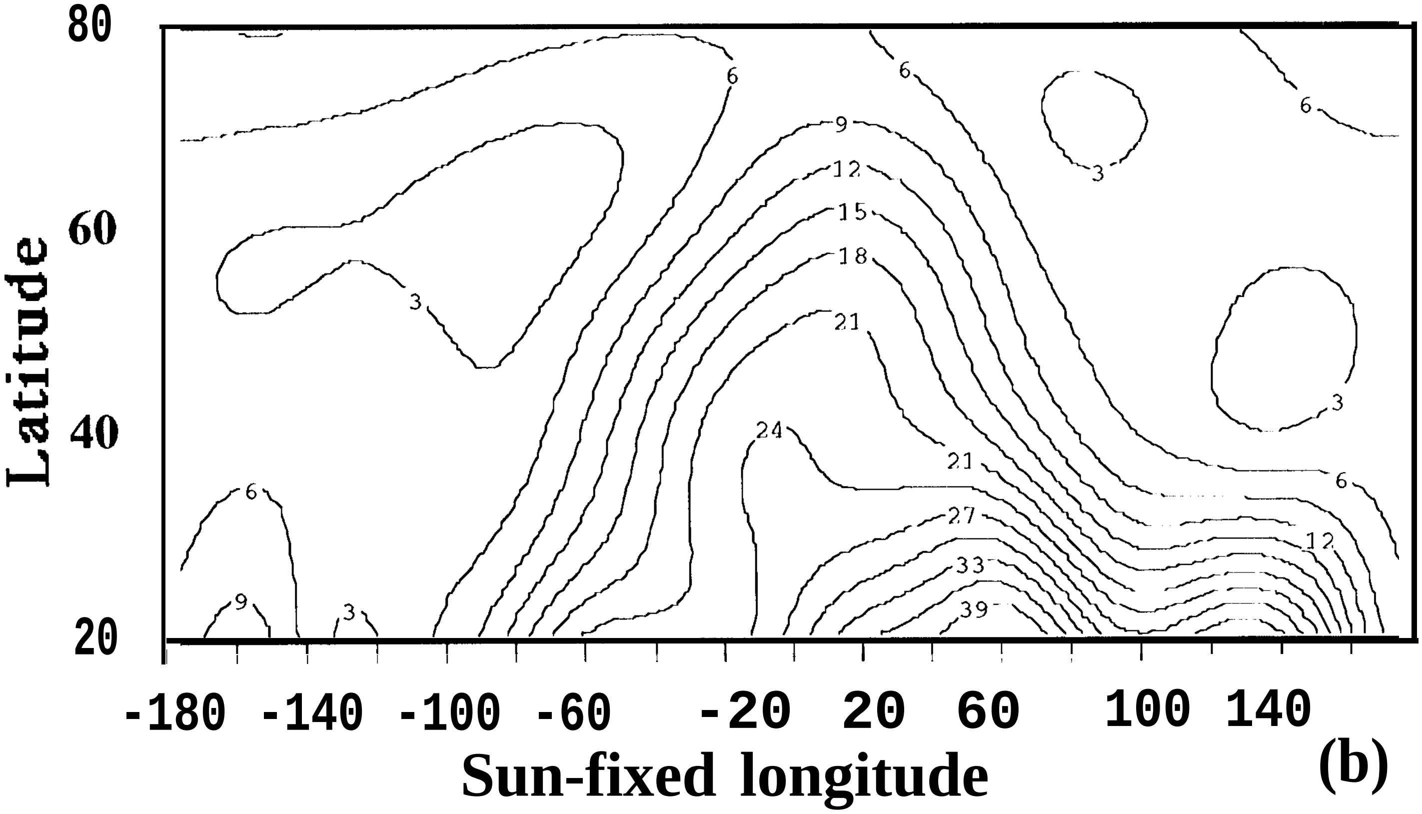
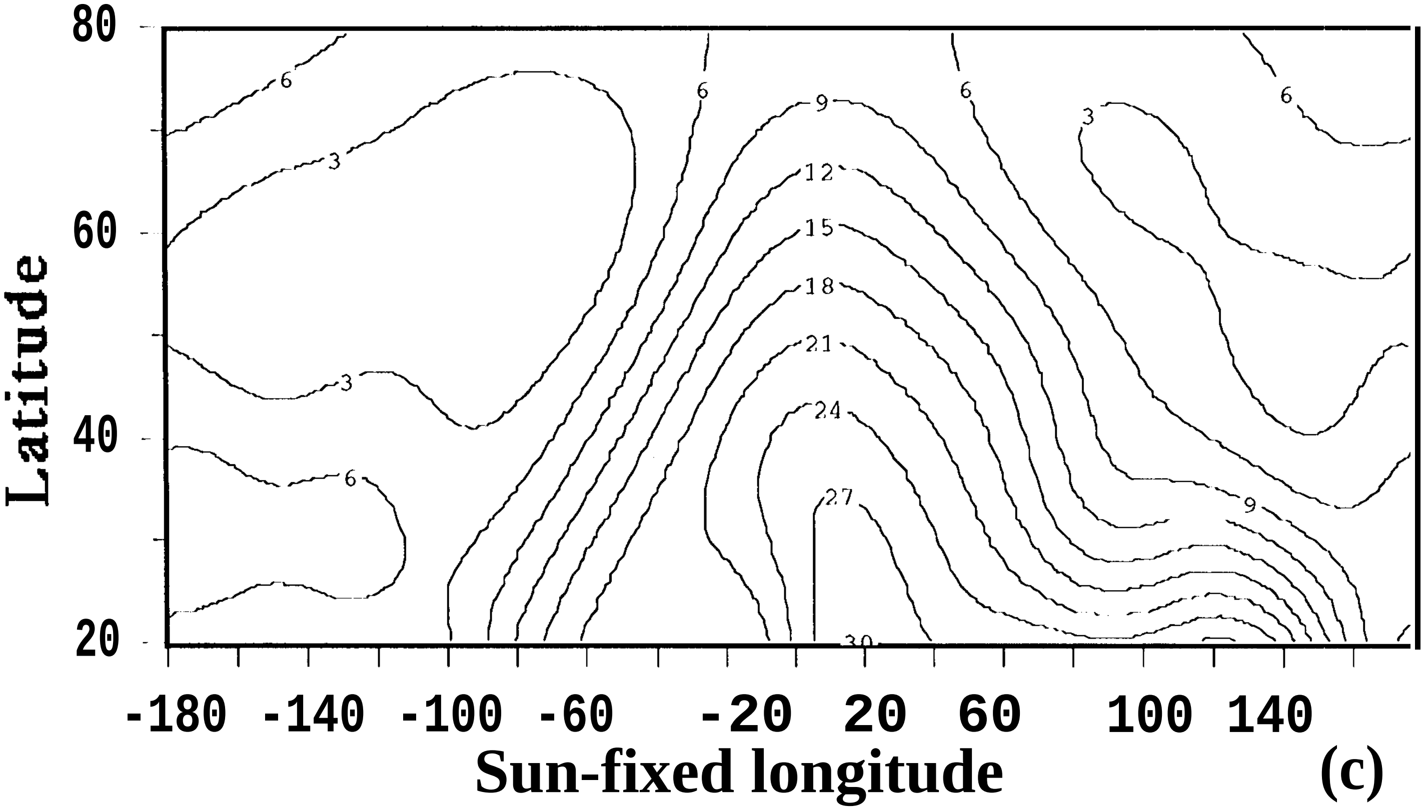


Figure 4 ——— Global ionospheric TEC distribution for January 4-5, 1993 derived from three 12-hour fits. Contours are labeled in units of 10^{16} el/m^2. (a) Fit of data from 0-12 UT on Jan. 4. (b) Fit of data from 12-24 UT on Jan4. (c) Fit of data from 0-12 UT on Jan 5.



(b)

Figure 4 — Global ionospheric TEC distribution for January 4-5, 1993 derived from three 12-hour fits. Contours are labeled in units of 10^{16} el/m^2. (a) Fit of data from 0-12 UT on Jan. 4. (b) Fit of data from 12-24 UT on Jan4. (c) Fit of data from 0-12 UT on Jan 5.



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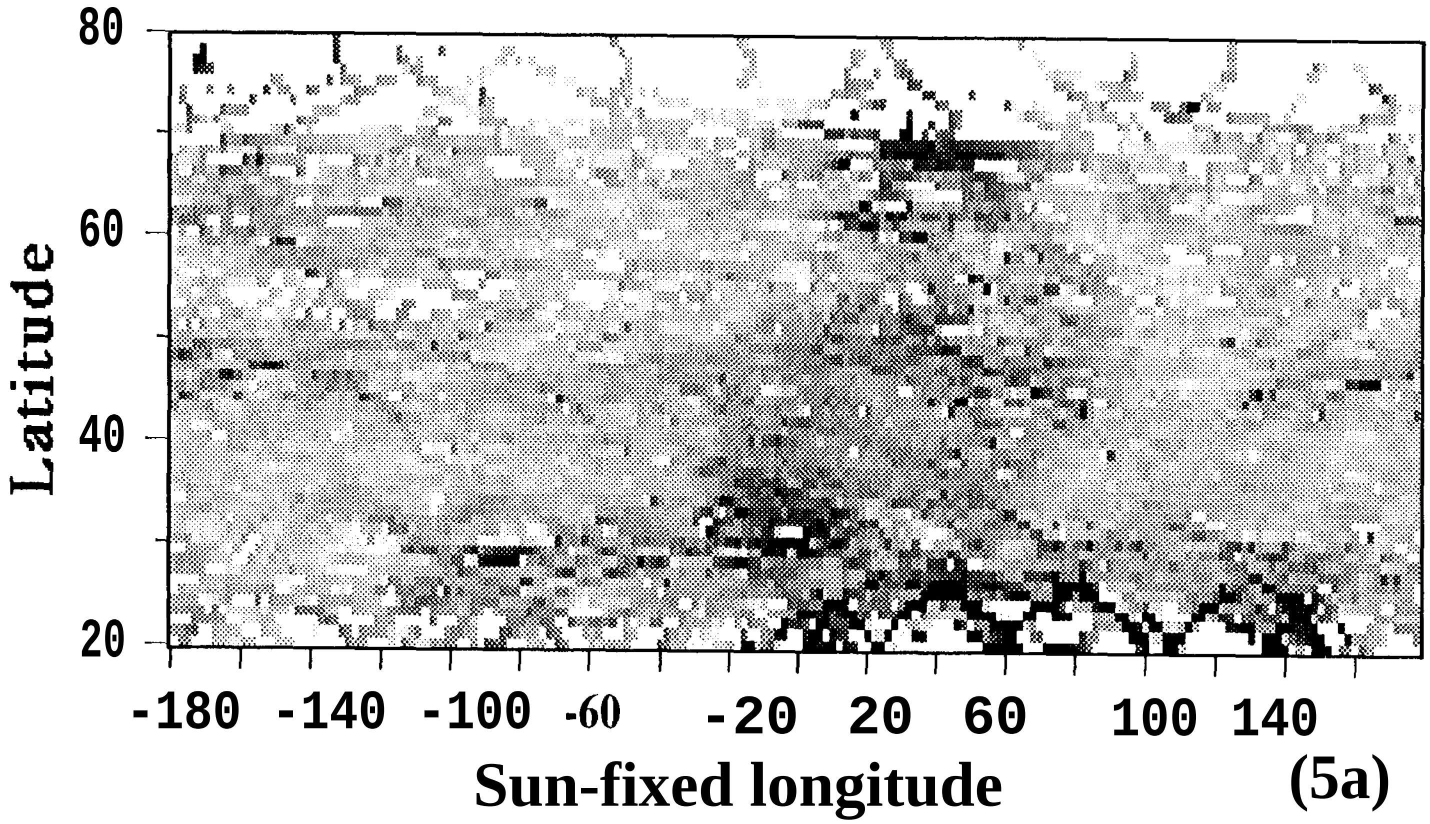
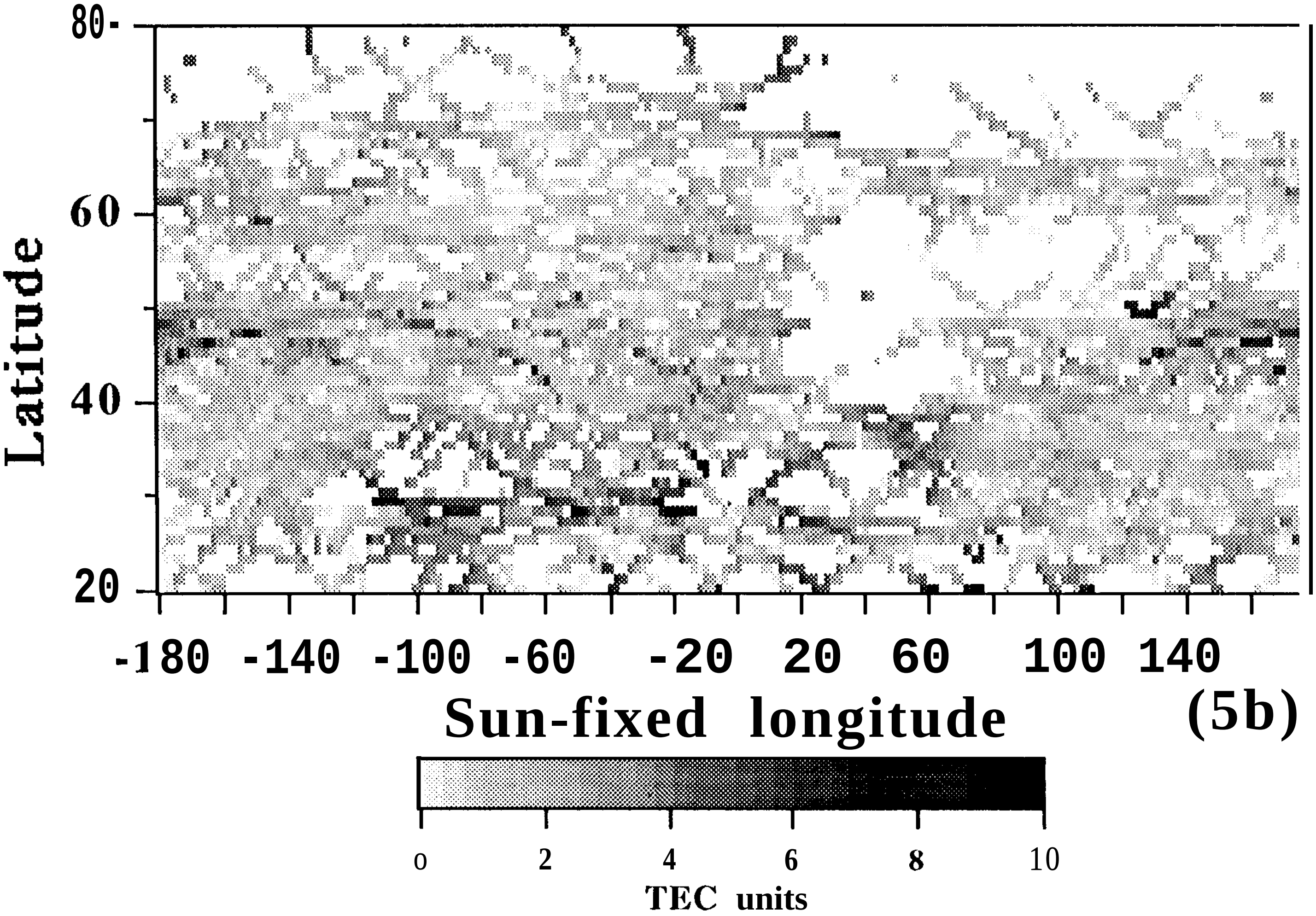


Figure 5 — Gray-scale map of fit residuals on Jan. 4, 1993. RMS residuals were accumulated into a one-by-one degree grid. White boxes are regions without coverage. The range is from O (light grey) to 10 TEC units (black). (a) Residuals for a 24-hour fit, (b) Residuals for a 12-hour fit using data from 0-12 UT.



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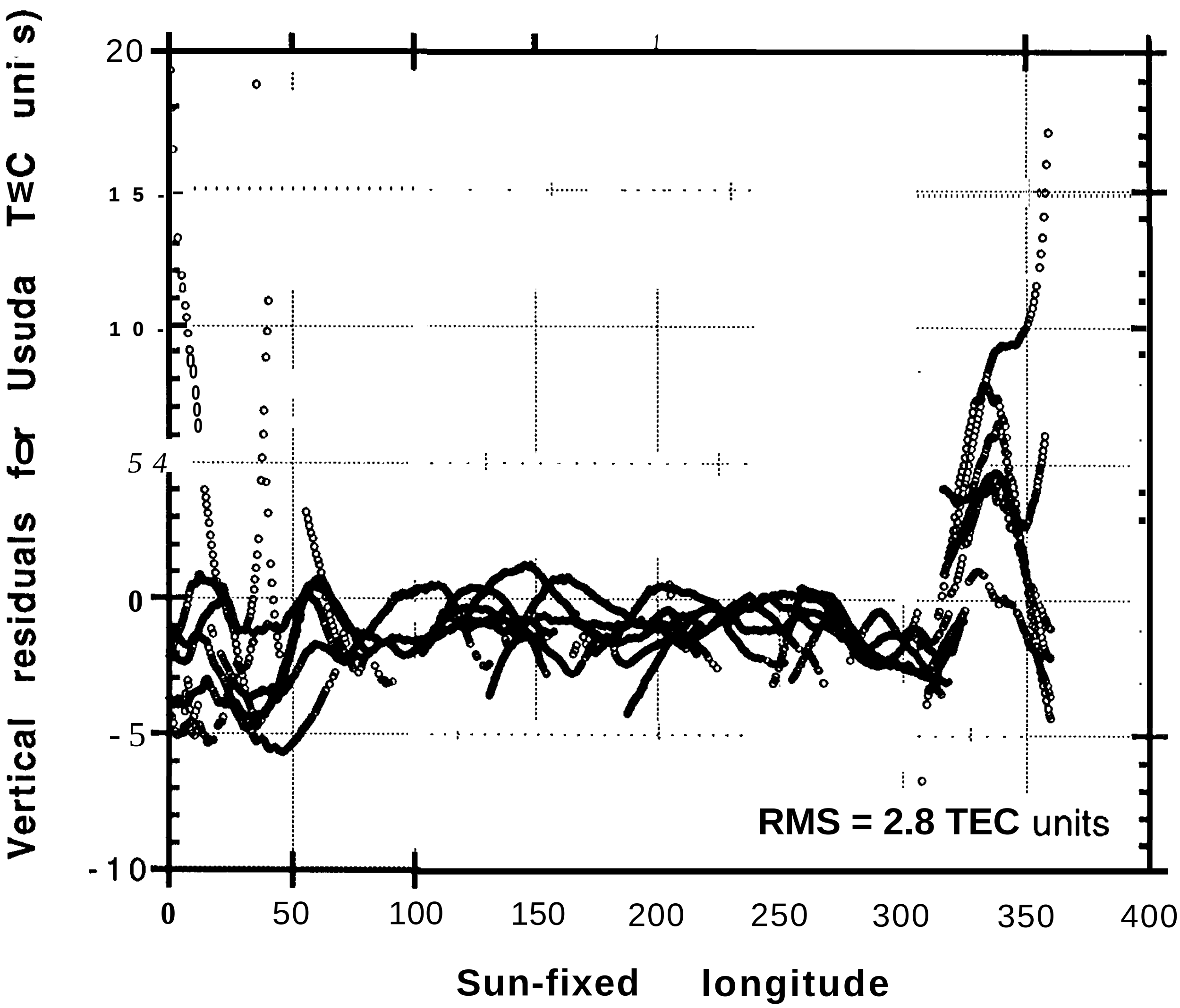


Figure 6 — Vertical residuals (observed mapped to vertical minus the fit) for the Usuda site on 93/01/05. The fit is a 24-hour fit excluding the Usuda data. The Sun is at zero degrees longitude.

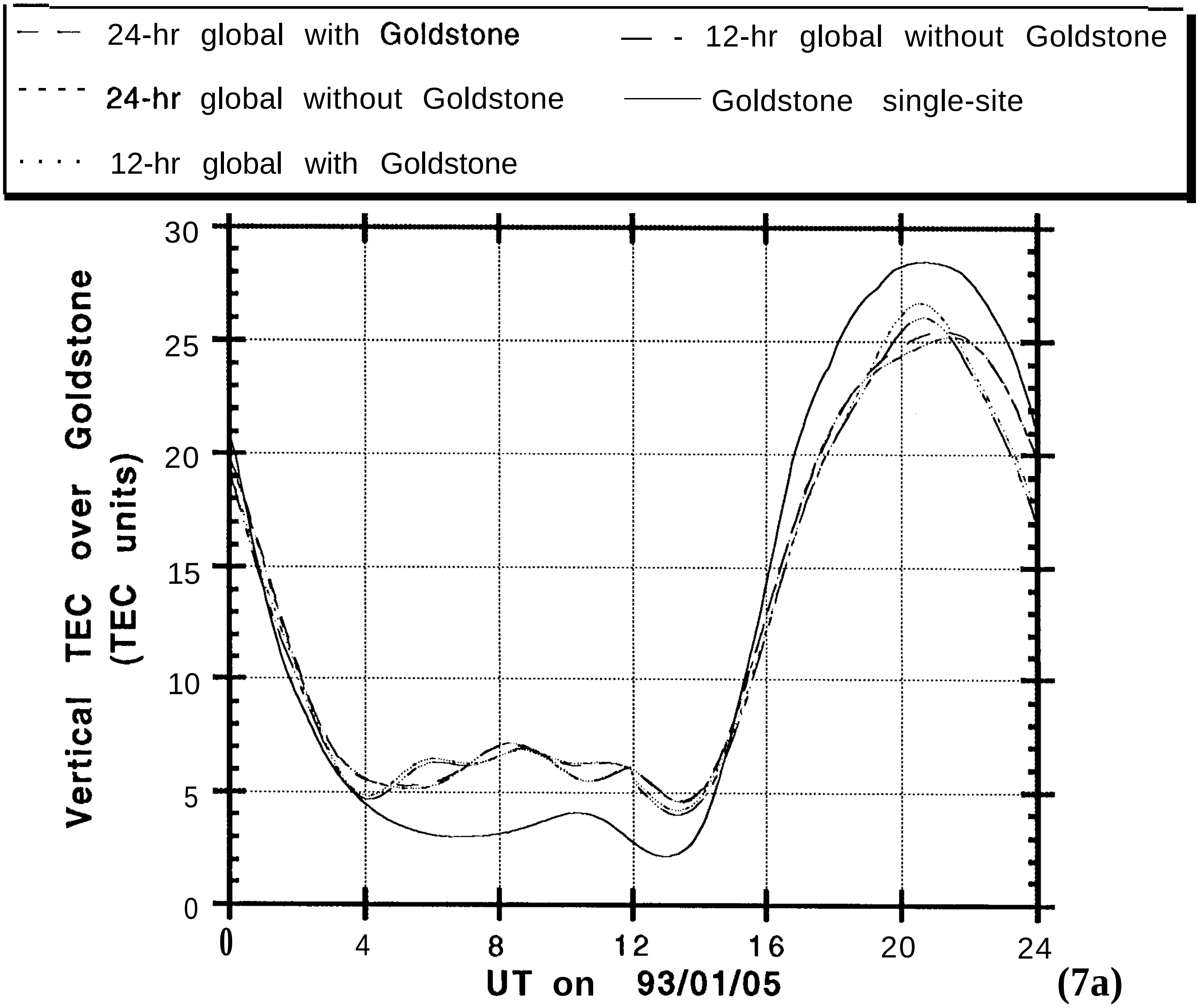
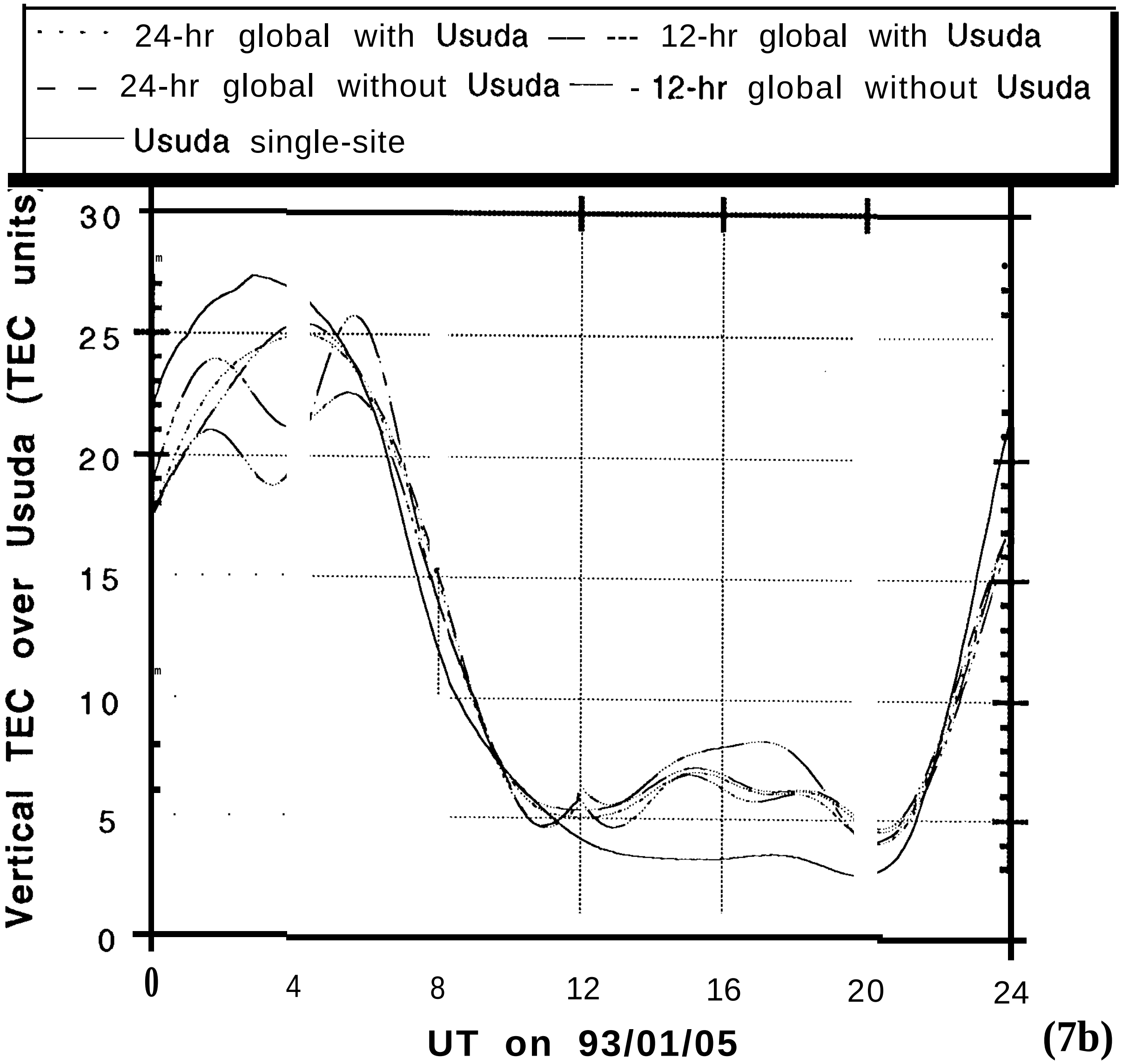


Figure 7 — Vertical TEC directly above (a) Goldstone and (b) Usuda during the 24 hours of Jan. 5 as predicted by five different fits. The solid line is the single-site fit and the rest are global fits. Notice that the global fits excluding the chosen site are within a few TEC units of the single-site fit,



(7b)

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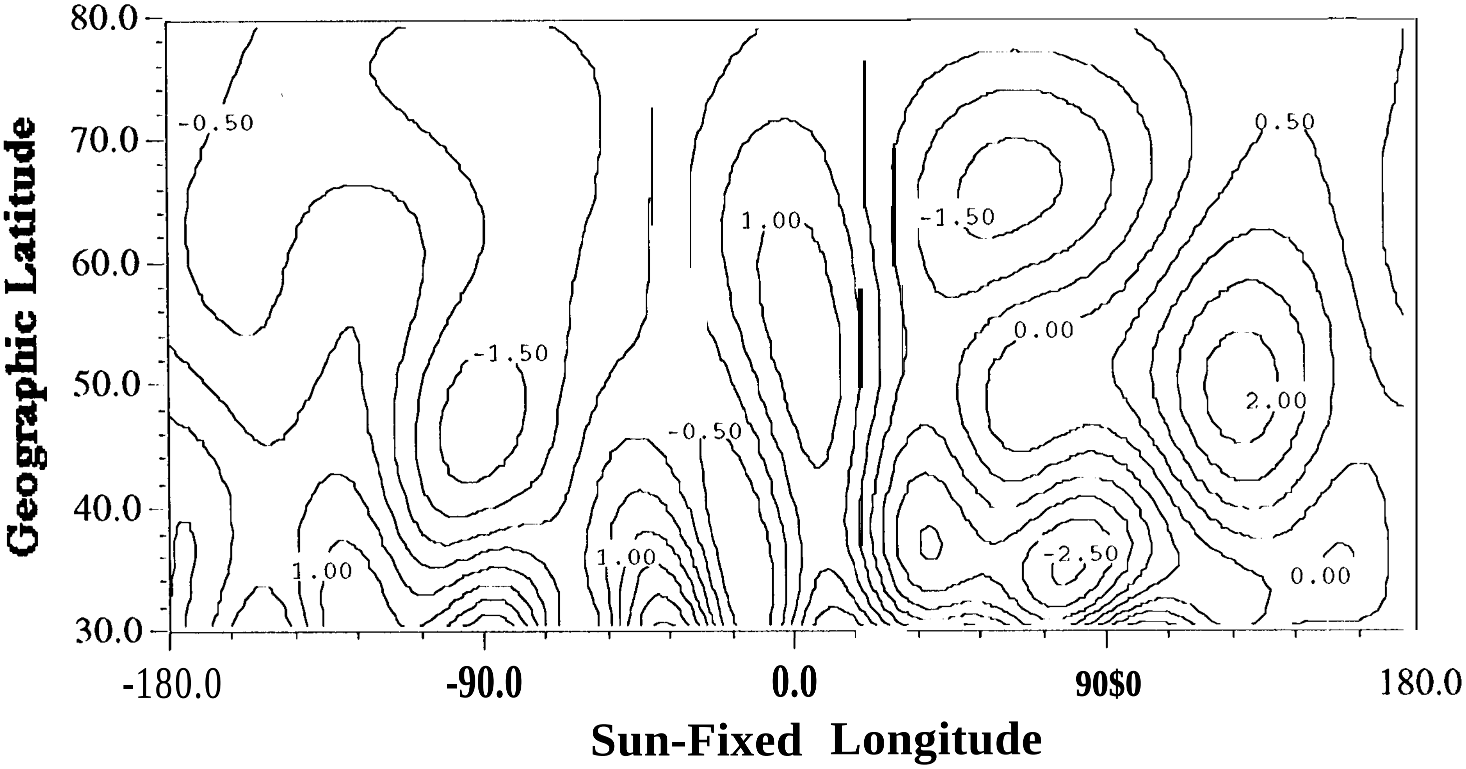

Figure 8 — The difference of two 24-hour TEC maps which differ in elevation angle cutoff: 20 degrees versus 10 degrees. The difference map is formed by differencing two one-by-one degree grids. Notice that the differences are small and zero mean which indicates that including data down to 10 degrees is not significantly altering the maps.